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High-speed cameras in sport and exercise: Practical applications in sports training and performance analysis

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Summary. *Technological advances applied to the world of sport have improved the experiences of participants, coaches and spectators. Specifically, high-speed cameras and slow-motion video have allowed for study leading to improved learning processes and performance in sports, as they have made it possible to analyze movement and evaluate various factors involved in these processes. Thus, these cameras have helped supply additional feedback for training and learning sessions. Moreover, they constitute a valuable tool for both researchers and coaches to assess performance and measure the duration of events, velocities, accelerations and forces that are generated in human movement. This article aims to deepen readers' knowledge in this area. It analyzes the various tools on the market, as well as smart mobile phones and applications based on the use of the camera, often high-speed cameras. It also makes reference to software used for movement analysis. The article seeks to highlight recent research that has applied this technology and to suggest affordable and valuable practical applications for improving training and teaching processes in modern sport.*

Keywords: *slow motion; human movement; acute learning; motion analysis*

Càmeres d'alta velocitat en l'esport i l'exercici: aplicacions pràctiques en entrenament esportiu i anàlisi de rendiment

Resum. *Els avenços tecnològics aplicats al món de l'esport han permès millorar les experiències de practicants, entrenadors i espectadors. Les càmeres d'alta velocitat i el vídeo a càmera lenta han permès estudiar, conèixer i millorar els processos d'aprenentatge i el rendiment en els esports, analitzant el moviment i valorant diversos factors en aquests processos. Així, aquestes càmeres han contribuït a millorar el feedback a les sessions d'entrenament i d'aprenentatge. A més, constitueixen una eina valuosa pels entrenadors i investigadors alhora de valorar el rendiment i quantificar la durada dels esdeveniments, les velocitats, les acceleracions i les forces que es generen en el moviment humà. Aquest article analitza les diverses eines que hi ha al mercat, així com els telèfons mòbils intel·ligents i les aplicacions basades en l'ús de la càmera, sovint d'alta velocitat. També fa referència als programaris per a l'anàlisi del moviment més utilitzats. Finalment, presenta el últims estudis en els quals s'ha utilitzat aquesta tecnologia i suggerir aplicacions pràctiques, assequibles i valuoses per la millora dels processos de millora a l'esport modern.*

Paraules clau: *càmera lenta; moviment humà; aprenentatge agut; anàlisi del moviment*

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Introduction

The revolution in sports technology in sport is readily apparent to participants, practitioners and spectators alike. Nowadays, an important part of the economics of sport is related to new technological applications in this field. An endless series of new sensors, gadgets, software and applications have been created to provide users with greater accessibility, control and motivation to take part in physical activity, do sports and maintain healthy habits, contributing to the promotion of sports and fitness all over the world (Aniss, 2016; Haake, 2009). For instance, tracking applications have been widely used in outdoor sports and physical activity. Global positioning systems (GPS) and accelerometers are especially useful for establishing the amount of activity undertaken in disciplines such walking, trekking, cycling and running (Duncan, Badland, & Mummery, 2009; Van der Spek, Van Schaick, De Bois, & De Haan, 2009). Team sports have also used these types of technologies, which can serve to quantify the training loads and report statistical data on events, and for other purposes that are valuable to coaches and spectators (Coutts & Duffield, 2010).

Images represent one of the most important sources of information in sport. Sports training and conditioning sciences use images and video recordings for a wide range of purposes (Wilson, 2008). Moreover, other disciplines like education sciences, motor learning and sports media have also used images for their own ends, such as to enhance the efficacy of the learning processes and to heighten the spectacular nature of sport (Aniss, 2016). The process of introducing video into sport has recently taken a qualitative leap forward thanks to the use of high-speed cameras and slow motion videos for the purposes of training, learning and spectacle. Slow motion videos have made possible an improved experience of observing and analyzing the movements (Lee, 2014). They have allowed coaches to improve their ability to correct athletes' technique and athletes themselves to observe their own execution of movements. Furthermore, broadcast companies have used high-speed cameras to make sports broadcasting more attractive to the audience.

A high-speed camera is a video camera able to record a higher number of frames per second (fps or Hz), which is different from slow motion reproduction. Its main characteristic is its high sample rate acquisition system. A 'normal' commercial cameras records at 25 or 30 fps (with a possible widening of the images), while high-speed cameras do so from 100 to 1000 fps. Together with a lens and optical characteristics, the sample rate determines the extent to which a camera can gather precise visual information about body movements and objects like balls and other artefacts (Shum & Komura, 2005). A few years ago, the cost and availability of this type of cameras put them out of the reach of athletes and practitioners. The electronics and lenses of these cameras were expensive and only certain advanced labs were able to afford them. At the present time, the situation has changed and the technological revolution has brought with it high speed cameras at low cost. Important manufacturers like Casio©, Sony© or Nikon©, JVC© and GoPro© have incorporated electronic components to convert those conventional compact cameras into high-speed recorders. As a consequence, their use has extended through the world of sport in different applications. Even more recently, the emergence of smart phones and the corresponding video technology have put high-speed cameras in the pocket of an increasing number of people. The new smart phones from Apple© HTC© or Samsung© include high-speed video cameras with a sampling rate up to 240 fps. This 'total availability' of such technology has opened up many new possibilities to coaches and teachers concerned about improving the quality of their work. Technology manufacturers are sure to continue down this path which means that the use of these devices will be extended further.

The present paper focuses on video technology in sport, its evolution and current characteristics. It covers the irruption of high-speed cameras in the most popular electronic devices, with a special focus on the use of all kinds of supporting software and applications in the sports domain. Moreover, the paper revises the most recent research that has incorporated the use of these devices into their methodology.

Slow motion: From lab biomechanical analysis to widespread use in sport

Video can present images a coach cannot see with the naked eye. For example, high shutter speeds, stop motion, and high frame rates provide more images and may help capture pivotal frames, such as the moment of take-off in jumping or of impact in ball striking (Wilson, 2008) as many times as the coach may need to help improve an athlete's technique. Indeed, slow motion has provided the possibility to improve the observation of the nature of movements, reporting data on the crucial moments of such actions. This is far from a new idea, and it is worth noting that as far back as 1936 Barstein had suggested the use of these procedures to analyze running technique (Gazienko & Fejgenberg, 2000). Since the 1970s, when the first electronic motion analyzers became commercially available, the affordability, capabilities and features of high-speed video and electronic cameras have improved dramatically (Balch, 1999). From the beginnings to 2005, only the sophisticated biomechanical laboratories could afford high-speed cameras. The evolution of such devices has been reflected in their different layouts, characteristics and uses (Figure 1).

Around 1980, a series of new features were introduced in motion analyzers. In 1979, a 200 fps camera was developed together with color capture, and long durations were possible. In 1980, Kodak introduced a third generation motion analyzer, the SP2000 motion analysis system. This revolutionary high-speed video device recorded monochrome images at 2000 fps. The

Figure 1. Evolution of commercial high-speed cameras.

next significant technological breakthrough came in 1986 with the Kodak EktaPro 1000, which had many advanced features, including a low-cost, high-performance tape transport system, dual camera operation, a new control interface and time code synchronization. The dual camera operation allowed for the viewing of images from either camera or displayed them both on a split screen. The cameras could even operate at different frame rates. Magnetic recording technology has been used in the last three generations of motion analyzers. However, the technology suffered from the recording limitations inherent in magnetic tape-based motion analyzers. Such motion analyzers were not only limited in the length of time they could record, but also because during their rewind cycle, the magnetic tape was not positioned for recording and an event occurring at this time could not be captured. Another problem with these cameras was that there was a lag time associated with their ability to stop. The time required for starting and stopping made these motion analyzers inefficient for short recordings. The next generation of high-speed cameras were built with Dynamic Random Access Memory (DRAM) and capable to store digital images. Over the last two decades, DRAM integrated circuits have been increasing in storage density and decreasing in storage cost per frame. Recently, DRAM architectures have been pushing the memory densities to a level where their use in high-speed cameras is cost effective. The subsequent technological battle was the quality of the images. Improvements in the electronics and optical features related to resolution, sensitivity and information storage came next. The revolution has kept going, with more suitable gadgets including the most advanced features being produced at a low cost, size and weight.

New gadgets, new trends

Typically, though, extensive equipment is still needed to capture images in high speed. Average video cameras capture between 24 and 30 frames per second, with many cameras now pushing that to 50 or 60 fps in 1080p HD. As mentioned, early high-speed cameras used film to record the high-speed events, but today high-speed cameras are entirely electronic, using either a charge-coupled device (CCD) or a CMOS active pixel sensor, recording typically over 1000 fps into internal memory and playing images back slowly to study the motion for scientific study (Balch, 1999). One of the most important factors for considering the quality of the devices is the sample rate and the lens features balance. Each user needs a certain number of frames per second required to collect the information for the analyses, as well as good picture definition to ensure precise observations. It is also important for users to consider the brightness of the environment to observe all details of movements. For instanceif the resolution and bitrate of its video compression are lowered, the iPhone 6 can record 240 frames per second at 720 pixels (p) high definition (HD), enough to slow down playback to a tenth of the original speed and still play it back at a regular cinematic 24 frames per second. Recently, the new Iphone SE provides the same features at a lower cost. However, Casio©, (Casio Computer Co., Tokio, Japan) is the pioneer manufacturer in introducing high-speed technology in their photography products. The Exilim HS™ models include the best features for a high-speed video quality experience. From the first Exilim EX-F1™ model to the recent Ex ZR3500™ model, the brand's products have gained in sensitivity, memory and speed. Other manufacturers like Photron©, with its Fastcam™ series, Phantom™ series by Ametek© and Fastec Imaging™ are also competing for supremacy in this market. Recently, Sony©, with its RX 100 series, has entered the club of high-speed camera manufacturers. The brand has incorporated a new 42.4 megapixel backside illuminated CMOS sensor that can shoot at up to ISO 102,400. The A7R is an interchangeable lens camera with a full-frame 35mm sensor and works with Sony›s FE mount lenses. Sony says the new camera has a new shutter that reduces vibration by up to 50 percent. Elsewhere, JVC© is offering the JVC GC-PX1 High-Speed Camera, which includes the capability of shooting bursts at 60 per second for 144 shots, ISO sensitivity up to 6400, recording at 300fps in 640 x 360 resolution. In short, the brand has incorporated high-speed technology as a crucial feature of its new creations. The passion for slow motion and the chance to observe natural phenomena from another point of view is no turning back.

Movement analysis software

The benefits of the new characteristics of the high-speed video cameras wouldn't be visible without the use of various software programs to analyze the recordings. In recent years, the features of this software have increased exponentially and today are a range of excellent programs that are available at no cost. These programs provide common tools for movement analysis. They even allow for side-by-side comparisons of techniques by doubling the video player. This feature

Figure 2. Stromotion and simulcam of Dartfish™.

sometimes permits lets users synchronize videos and view the same action recorded by two cameras from two different points of view, for instance from the frontal and lateral plane. With this kind of software we are also able to add drawings and comments to the video. Moreover, we are able to make some calculations in certain frames of things like angles or distances (some of them require spatial calibrations). Another possibility is to zoom in on certain part of the picture, for a better observation of the details of the video, and to make image adjustments like brightness and contrasts. Recently, different developers have implemented solutions for tracking a given point of the image. This feature shows the trajectories of the limbs, balls and any other chromatic contrasted point. At the end, a pre establishment of the video sample rate (fps) allows for the precise calculation of the time between events or of the duration of phases of movement phases. This function constitutes a valuable and precise chronograph for athletes and coaches (Figure 2).

The most commonly used software in the sport domain is Kinovea (Creative Commons 3.0. license). Kinovea is a completely free (available at www.kinovea.org) and open source video player that lets users analyze the technique of the different sport skills. Other programs include Tracker (GNU General Public Licence 3, Open Source Physics), a free video analysis and modeling tool, and Dartfish©, another interesting solution for video capture and analysis. Beyond all the features mentioned above, the software includes an interesting function called 'stromotion' that marks and fixes certain key frames on the image to track certain key points of the movement. Dartfish™ also permits users to insert a video into another video in function the called 'simulcam' with the objective of comparing two different executions of the same movement (Figure 3). It is certainly useful in case of model comparisons. Angle tracking is a quite common function of this type of software, and also Kinovea and Tracker allow for the tracking of angles of certain movements around a joint and the detection of angle variations during a movement (Figure 3). But the traditional performance analysis system is Ariel© by APAS™, which was the first computerized movement analysis system available. Now, the system includes software for a set of two or more high-speed cameras in a complete movement analysis system. Like other systems, Ariel permits complete 3D analysis with video modelling and collects data about position, speed and acceleration of every part of the body in a given movement. The software also permits users to digitalize movements to create models and identify the vectors of the forces exerted by the athlete. Moreover, the system offers the possibility to track movement by measuring the position from the suit with markers at the key points of the body. The solution plots all the data in real time and synchs

Figure 3. Angle measurements with Kinovea and Tracker.

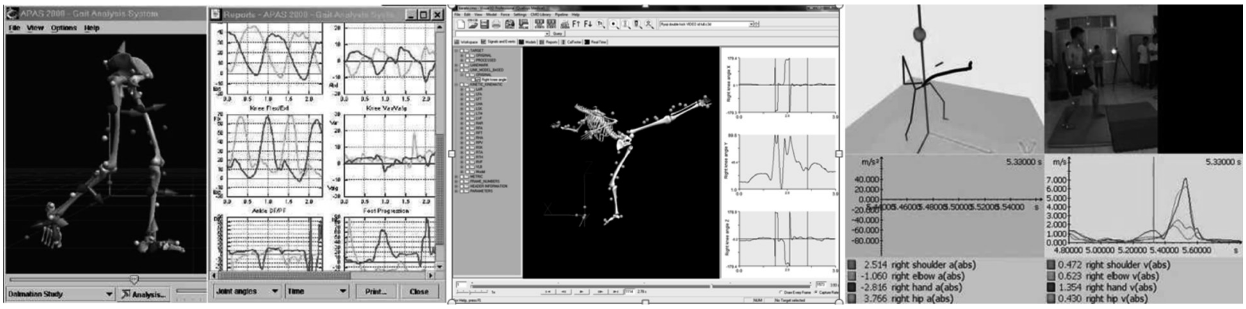

Figure 4. Screenshots of Ariel™, Quintic™ and Qualysis™.

it with the video. Similarly, Quintic™ provides the possibility for a complete 21-point automatic and manual digitalization of movements. The digitalization allows for the calculation of speed, accelerations and angle rotations of the limbs, as well as creation of anatomical models. The system is also able to synchronize multiple high-speed cameras. Qualysis™ is a multi-camera optical motion capture system or an eight-sensor, 3D electromagnetic motion capture system to home in on patterns of human movement. The software provides solutions to quantify movement and create models. Additionally, Qualisys Track Manager tracks objects automatically in real-time, and 2D, 3D and 6D camera information is displayed, allowing for instant confirmation of accurate data acquisition. Such software programs are able to integrate coded information from a system using a number of high-speed cameras displayed in a lab, all without needing to upload heavy video files. This makes possible the analysis of lengthy sequences. All these systems are spearheading progress in motion analysis in biomechanics (see Figure 4). But recently, Tracker, the free Open Source Physics project, has started to provide similar solutions to those that Ariel and Quintic offer. Modelling features and sophisticated video analysis have been included in a useful system that is able to analyze all video formats and collect all variables and data from the models.

At the same time, the smart phone revolution has brought with it dozens of simple video analysis applications, which have emerged in the Android and Apple stores. Most of these apps include some simple functions like zooming, angle and line drawings, timing and video comparisons (Figure 5). Examples of the most referenced and used are CoachMyVideo, Dartfish Express, Technique, SloPro, Coach Eye, ICoach View or Shot Coach. These apps use the phone cameras and promote video sharing communities. All of them are linked with social networks and constitute a useful pocket solution for coaches and athletes in the field.

High-speed cameras in recent sports training research

All biomechanics studies use the video cameras with high sampling frequency, which can be found in most laboratories. In addition to this research, there have been some interesting studies using high-speed video cameras with simple motion analysis, as practitioners might do in the field. This is precisely the sort of research we want to discuss in this paper, and in so doing we want to give some practical ideas coaches and athletes will be able to apply in their daily work. One of the first focuses of interest in using the high-speed cameras was the assessment of the ground contact times in running and sprinting activities. Knowing the reactive ability of the athletes when contacting the ground constitutes an interesting indicator of sprinting performance. Rimmer and Sleivert (Rimmer & Sleivert, 2000) investigated the effect of conditioning training pro-

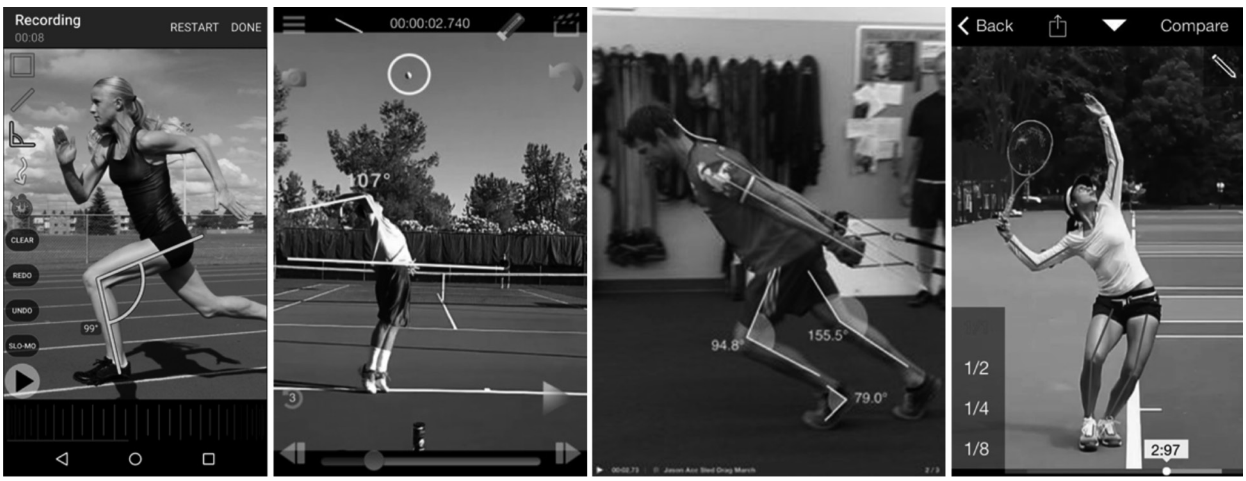

Figure 5. Screenshots of CMV+, Coach's Eye, Dartfish Express and Technique.

grams on the improvement of the ground contact times using a 200 fps high-speed camera. They concluded that a sprint-specific plyometrics program can improve 40-m sprint performance to the same extent as standard sprint training, possibly by shortening ground contact time. Data collected by a high-speed camera were used to assess stride length, stride frequency, step flight times and contact times in a study of the effects of resisted sled towing on sprint kinematics in ruby players (Spinks, Murphy, Spinks, & Lockie, 2007)the effects of acceleration training, or the effectiveness of different training modalities. This study examined the effects of resisted sprint (RS. The factors that contribute to sprinting performance has been assessed in recent years using high-speed cameras (Bergamini et al., 2012; I. N. Bezodis, Kerwin, & Salo, 2008; N. E. Bezodis, Salo, & Trewartha, 2010; Bradshaw, Maulder, & Keogh, 2007; Lockie, Murphy, Schultz, Knight, & Janse de Jonge, 2012)or thereof derived, for the identification of foot-strike and foot-off instants of time and for the estimation of stance and stride duration during the maintenance phase of sprint running. Maximal sprint runs were performed on tartan tracks by five amateur and six elite athletes, and durations derived from the IMU data were validated using force platforms and a high-speed video camera, respectively, for the two groups. The IMU was positioned on the lower back trunk (L1 level. A painstaking stride analysis provides information about acceleration, braking, reactivity and forces exerted on the ground by the athletes. With such information, coaches are able to guess where and how the sprinters lose time and provide feedback to their athletes. Recently, a simple method using commercial high-speed compact cameras was proposed to assess power, force, velocity properties and mechanical effectiveness in sprint running (Samozino et al., 2016). This method was validated against a force platform and a radar gun, and it represents a valuable tool for coaches. In addition, the study inspired the creation of a new mobile application called MySprint to analyze some of the aforementioned sprint variables. With a similar idea, Buscà, Alique, Salas and Hileno (Buscà, Alique, Salas, & Hileno, 2012) proposed a simple method to assess the specific short-sprint ability for beach volleyball defensive actions. A high-speed camera was used to measure the time of different tranches of a new test on the sand. Frame by frame counting allowed the authors to determine the time spent on each part of the test and, in consequence, to establish the player's profile and the connections with other performance variables such as jumping (Buscà et al., 2015). The method for assessing flight time on the sand was, again, a high-speed camera.

In addition to sprinting, weightlifting is also using high-speed video analysis to calculate velocity, power and forces exerted. Following the path of the barbell marking the position of points of interest (knee, hip, center of a barbell plate, etc.) some software permits users to register the 2D coordinates of each digitized point. When the points of interest are digitized for all pictures of the movement sequence, parameters such as displacement, path of motion, velocity, joint angles and angular (rotational) velocities can be calculated by the associated computer program (Garhammer & Newton, 2013). Such applications of high-speed cameras have been used, for instance, in comparing different techniques of powerlifting in exercises like squats, deadlifts or clean and jerk (Hales, Johnson, & Johnson, 2009)knee, and ankle. Paired (samples. Furthermore, in throwing sports, high-speed video has offered valid and reliable data about the kinematics of handball throw, tennis serve and volleyball spike (Wagner et al., 2014)the adaptations to different sports are not well understood. The aim of the study was to analyze upper-body kinematics in the team-handball throw, tennis serve, and volleyball spike, and to calculate differences in the proximal-to-distal sequencing and joint movements. Three-dimensional kinematic data were analyzed via the Vicon motion capturing system. The subjects (elite players.

The field of decision-making assessment and analysis has also taken advantage of the benefits of high-speed video technology. For instance, a high-speed video camera interfaced with a video recorder was used to study rugby players, recording the subject's change of movement direction relative to the tester. The number of frames between the tester's and player's movement initiation enabled the player's decision-making time to be recorded to within ± 5 ms for each trial (Gabbett & Benton, 2009)no study has investigated the reactive agility of these athletes. The purpose of this study was to investigate the reactive agility of rugby league players, to determine if this quality discriminated higher and lesser skilled players. Twenty-four elite (mean+/-S.D. age, 24.5+/-4.2 years. Similarly, this technology has been used to determine the effects of training change-of-direction speed and small-sided games on performance in Australian Football players (W. B. Young & Willey, 2010; W. Young & Rogers, 2014). Elsewhere, Buscà and Febrer (2012) have analyzed the temporal fight of volleyball high-level setters and the opponent middle-blockers to help them gain an advantage in attack construction situations and blocking, respectively. A frame-by-frame high-speed video sequence analysis was used to calculate temporal descriptive data from setting trajectories and the anticipatory behaviour of the middle-blocker. Moreover, Hileno and Buscà (2012) studied the attack coverage patterns in volleyball providing a sequential analysis only possible with the sampling rate offered by high-speed video.

Video and high-speed cameras in movement learning research

There have been many investigations into the role of visual strategies in motor learning, such as observation or imitation. Most of them have been based on video feedback, which can take on different forms. Referring to Boyer et al. (Boyer, Miltenberger, Batsche, & Fogel, 2009) and to Dowrick (Dowrick, 1999, 2012)examining the use of self modeling (mostly in the video medium, Amara et al. (2015) distinguish between three types of video feedback used for movement learning: self-modeling, expert-modeling and model superposition. The first is a model of observational learning in which the observed and the observer are the same person. In the second case, the observed and the observer are different subjects, while model superposition features a mix of both. Cassidy et al. (Cassidy, Stanley, & Bartlett, 2006) stated that in order to garner increased benefits from the use of camera technology and the information it provides, there must be a strong relationship between the skills being taught and the content of the video. Moreover, it is essential to take into account what is being observed, ihow it is observed and the identity of the observer And it must be stressed that before using such technology for giving feedback, a code has to be established to transmit the information.

In spite of the depth of the investigation conducted to date in physical education and sport settings (Siedentop, 1994), there is still a lack of studies of the visual feedback about complex sport skills learning processes (Sigrist, Rauter, Riener, & Wolf, 2013). Todorov et al. (Todorov, Shadmehr, & Bizzi, 1997) reported that subjects who received visual feedback in an experimental setting achieved better performances than the control groups, although the latter group received 50% more practice in the real task. In most studies, visual feedback has been compared with other types of feedback such as verbal, tactile and multimodal feedback (Sigrist et al., 2013), while taking into account the moment at which such feedbacks are provided, whether concurrent or terminal. One such investigation was carried out by Rhoads (Rhoads, 2012) to study the effects of different visual and verbal feedbacks on spiking performance in volleyball. The author found that both modalities improved the performances in a significant way but did not report any significant differences between them. Menickelli (Menickelli, 2004) showed scientifically relevant differences between four different types of feedback (presence/absence of instructor/video feedback) aimed at teaching a standard flying disc throw. According to the results, both self- and instructor-controlled video feedback proved more effective than either self- or instructor-controlled verbal feedback when it came to learning a multiple degrees-of-freedom skill. Furthermore, Guadagnoli et al. (2002) tested speed and accuracy in golf swing execution using the variables of video feedback, verbal instructions by an expert coach and self-guided instructions and found that the use of video feedback was significantly beneficial.

All the aforementioned studies were based on the use of real time video feedback. In fact, high-speed cameras can prove very useful for this kind of investigation since they allow for the reproduction of video feedback in slow motion. Al-Abood et al. (Al-Abood, Davids, Bennett, Ashford, & Marin, 2001) were among the first investigators to use such devices. Their goal was to assess the effects of slow-motion demonstrations, in comparison with real-time demonstrations, on the acquisition of movement coordination and control of an aiming task, which consisted in throwing darts towards a target with the dominant arm. The participants were divided into two groups: the real-time-videotape group and the slow-motion group. The study consisted of two sessions: one for acquisition (made up of 100 trials) and another for retention (20 trials). After every 20 trials, the subjects were allowed to rest for two minutes, and every one of them received visual feedback after each trial. The results of the study showed that when the subjects already have good knowledge of the movement, slow-motion video feedback allows them to derive more benefit from the demonstration, without causing any interference with absolute timing and force, two of the parameters of movement control. Another study analysed the influence of slow motion on movement learning among young gymnasts (Boyer et al., 2009). The subjects were asked to observe expert model videos and self-execution recordings, and the feedback was provided by slow motion as well as normal reproduction of the sequences. The investigators found that video modeling, self-execution visualization in slow motion and verbal instructions are very likely to reduce the number of learning sessions needed to acquire a given complex movement skill. Recently Amara et al. (Amara et al., 2015) studied the effect of video modeling on learning hurdle racing skills and used slow-motion video as a tool to improve the motor learning process. The study confirmed the benefits of the use of new devices linked to the evolution of information and communication technology (ICT), such as high-speed cameras.

Yet there remains an evident lack of studies demonstrating the benefits of using the slow motion feedback for improving the learning processes, and as a result new experimental designs investigating the acute and long term effects of video feedback are necessary to establish new behavioral patterns for coaches and athletes in technique acquisition sessions. This is even more important in the first steps of the motor skill acquisition processes in beginners.

High-speed cameras in sport training and performance: Practical applications

Jump assessment

Flight and ground contact times have been used for four decades as indicators to assess jumping ability and force/power production of knee extensors (Bosco, 1995). Timing methods using precise chronographs like contact mats or infrared lights connected to microcontrollers have supported solutions such as Musclelab©, Ergojump®, Axon Jump®, Smart Jump from Smartspeed™ and Just Jump from PowerSystems™. Recently, high-speed video has been replacing contact mat-based methods in a more accessible and usable tool. An Iphone app called MyJump has recently been developed to harness the possibilities offered by the

Figure 6. Screenshots of MyJump mobile app.

new generation of high-speed cameras of smartphones (Balsalobre-Fernández, Glaister, & Lockey, 2015). Determining the moments the feet take off and land, the app calculates the flight time and the jump height using the equation described in the literature (Bosco, Luhtanen, & Komi, 1983). The method used by the app was found to be valid and reliable against a force platform-based method (Balsalobre-Fernández et al., 2015) (Figure 6). A Casio® ZR1000 HS EXILIM camera has also been used for the same objective, to measure flight time, in this case of beach volleyball players on sand (Buscà et al., 2015). Acceptable validity and reliability data were reported even considering the fact that the contact moments took place on sand. Kinovea analysis software was used to calculate the flight time and draw the criterion points. Recently, another mobile phone app called JumpPower™ has been created to provide height, force and power data on jumps. This app works by automatically tracking the trajectory of the face throughout the impulse and flight phases.

Sprint measurement

Other recent applications of high-speed cameras permit users to measure time, power, speed, acceleration and the mechanical effectiveness of line sprints (Samozino et al., 2016). The work of Samozino, together with that of Morin and colleagues, are based on the Iphone app MySprint™. MySprint™ uses the high-speed camera of an Iphone 5c, or later models, to determine the 10m-lap times of a sprint (Figure 7). The solution permits frame-by-frame playback, which allows for a precise determination of the exact moment when the athlete crosses certain markers placed at 10m intervals. A speed, acceleration, power and force profile is calculated according to the proposed method. Again, the camera was a Casio® HS F1 EXILIM. In addition to this app, other apps like SpeedClock™, Sprint Timer™ and Sport Watch™ can be used to detect the movement of the athlete over a given distance and report information about speed and acceleration.

Figure 7. Agility timer application with Kinovea.

Agility and change of direction measurement

Precise time intervals involved in different agility tests can be recorded with a high-speed camera. The different tranches of, for instance, the T-test (Semenick, 1990), Illinois test or RAT test (Sheppard, Young, Doyle, Sheppard, & Newton, 2006)the reactive agility test (RAT can be measured through the analysis of the amount of time spent on each phase of the test. For these tests, or another that was recently created for beach volleyball (Buscà et al., 2015), an interpretation of the ability for accelerating and braking, the efficacy of changes of direction and the differences between right and left running directions is possible. These data provide more accurate information to coaches about the inherent agility. In practical terms, a 240 fps camera is enough to record the circuit, with good light conditions needed for the recordings (Figure 7). It is necessary to establish precise criteria as to the start and the end of the test tranches, whether they are defined in terms of foot to ground contact or the passing of certain accurately placed marks (for instance Padullés, 2011). The chest or hips are appropriate places to put the markers for subsequent analysis with Kinovea or similar software.

Motion and technique analysis

Determining the sample rate of the recordings, many software programs permit an accurate analysis of times, angles and distances covered by an object on a certain specific plane. The simplicity with which programs like Kinovea implement such analyses constitutes a valuable tool for coaches and PE teachers. Using chronograph tools, practitioners are able to determine the ground contact times, the time spent on different phases of the movement, the hitting impact time of balls and the flight times of the steps in a sprint. Thanks to a several applications, simple kinematic analysis provides information about position, speed and acceleration of the limbs in a given movement. A space calibration is necessary to determine such variables. Kinovea, for example, is also able to track trajectories of a chromatically contrasted point in space. Thus, coaches can measure and control the execution of the athletes tracking barbells or strength training machine movements in different loads. This constitutes an interesting and accessible procedure for enhancing the control of the muscular power training processes using high-speed cameras. Furthermore, video recordings allow professionals to control the technique using the compass tool and other features of this kind of software.

Ball speed recording

High sample rate video also constitutes a valid tool for ball speed measurements in sports. Throwing and kicking sports require to measure balls' velocities. Different manufacturers have used radar technology for this purpose, but this may be inaccessible to sports practitioners (Buscà, Moras, Peña, & Rodríguez-jiménez, 2012; Moras et al., 2008). High-speed cameras, along with appropriate software or a frame counter, are accessible solutions. Using a known distance and video sampling rate, a precise frame count can provide valid and reliable speed data on balls and other projectiles assuming linear trajectories (Shum & Komura, 2005). Recently, the mobile phone app Speedclock™ has been created to track ball movements to report ball velocity, with results as accurate as those of a radar gun.

Conclusions

The revolution in the high-speed cameras in sports is evident. A wide variety of devices are available with a range of models, features and costs. Sport professionals and amateur coaches are increasingly using this technology to improve their learning and training experiences. In addition, new practical applications for monitoring and analyzing movement are constantly being developed for use not only in the laboratory, but also in the field. The fact that the camera is usually in the user's pocket as part of his or her mobile phone constitutes a big difference with respect to past uses of high-speed video technology.

In terms of research, the use of high-speed video has also expanded. Beyond the traditional use in biomechanics, it is now also employed as a precise stopwatch and a movement tracker, as well as to compare different models and detect movement. Lots of sport studies have already taken advantage of the benefits offered by the different models available, and this is just the beginning. to the future evolution in this area will move toward the use of more affordable devices and the full integration of high-speed video in mobile devices in a wide range of applications.

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